

TITLE OF THE INVENTION

THERMAL CONVECTION ACCELEROMETER WITH CLOSED-LOOP HEATER  
CONTROL

CROSS REFERENCE TO RELATED APPLICATIONS

N/A

STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH OR  
DEVELOPMENT

N/A

BACKGROUND OF THE INVENTION

The present invention relates generally to accelerometers, and more specifically to silicon micro-machined convective accelerometers.

Silicon micro-machined accelerometers are known which employ the principle of free convection heat transfer of a hot air bubble in an enclosed chamber to provide a measure of acceleration. Such devices comprise a chamber micro-machined in a silicon substrate, across which is provided a heater resistor and on each side of which is disposed a thermocouple. During zero acceleration, the temperature profile about the heater resistor is symmetrical such that both thermocouples sense the same temperature and therefore provide the same output voltage. Acceleration applied along the thermocouple-heater-thermocouple axis causes disturbance of the temperature profile due to free convection heat transfer, thereby causing an asymmetrical temperature profile which is sensed by the thermocouples to provide

output voltages that are different and a differential output voltage that is proportional to the applied acceleration. The differential output voltage typically requires signal conditioning to interface with the electronics of a particular application. Such signal conditioning is implemented using external electronic components and/or circuitry combined on the same substrate as the convective accelerometer.

Conventional silicon micro-machined convective accelerometers have drawbacks in that the sensitivity of these devices can vary. For example, the accelerometer sensitivity may vary with changes in the temperature of the silicon substrate and/or the local environment. The accelerometer sensitivity may also vary with changes in the power dissipated in the heater element.

It would therefore be desirable to have an improved silicon micro-machined convective accelerometer that is less sensitive to temperature and power fluctuations. Such an improved silicon micro-machined convective accelerometer would also have reduced power consumption.

#### BRIEF SUMMARY OF THE INVENTION

In accordance with the present invention, a silicon micro-machined convective accelerometer is provided in which a thermal acceleration sensor and associated signal conditioning circuitry are included in a single monolithic device. The device is formed in a silicon substrate and is preferably implemented using standard CMOS processes. Integrated within the single monolithic device is the thermal acceleration sensor, heater control circuitry, an instrumentation amplifier, clock generation circuitry,

voltage reference circuitry, a temperature sensor, and output amplifiers. The device can be packaged in a standard 8-pin integrated circuit package.

5 In one embodiment, an integrated convective  
accelerometer chip includes a convective acceleration sensor  
including a heater element and a pair of temperature sensing  
elements disposed on opposing sides thereof. The  
acceleration sensor is operative to produce a differential  
10 output voltage proportional to the magnitude of acceleration  
applied along an axis passing through the heater element and  
the pair of temperature sensing elements. The chip further  
includes amplification circuitry operative to extract an  
average output voltage from the differential output voltage  
15 produced by the acceleration sensor. The average output  
voltage provides a measure of the temperature gradient  
produced by the heater element. Still further, the chip  
includes control circuitry operative to produce a control  
output. In a preferred embodiment, the control output is a  
pulsed output voltage and operative to regulate the average  
20 output voltage, thereby regulating the temperature gradient  
produced by the heater element. Yet further, the chip  
includes a temperature sensor operative to produce a voltage  
level Proportional To the Absolute Temperature (PTAT) of the  
chip. Temperature compensation circuitry included on the  
25 chip or implemented externally to the chip can use the PTAT  
voltage level to compensate for changes in the temperature  
of the chip and/or the local environment.

In a preferred embodiment, the average output voltage  
and therefore the temperature gradient produced by the  
30 heater element are regulated by reading output voltages  
provided by the pair of temperature sensing elements,

comparing these voltages to a reference voltage, producing a pulsed output voltage having a pulse density proportional to the magnitude of a desired output voltage, and regulating the average output voltage using the pulsed output voltage.

5 Other features, functions, and aspects of the invention will be evident from the Detailed Description of the Invention that follows.

#### BRIEF DESCRIPTION OF THE SEVERAL VIEWS OF THE DRAWING

10 The invention will be more fully understood with reference to the following Detailed Description of the Invention in conjunction with the Drawings of which:

Fig. 1 is a plan view of an integrated circuit including a silicon micro-machined convective accelerometer device in accordance with the present invention;

Fig. 2 is a block diagram illustrating a convective accelerometer included in the device of Fig. 1;

Fig. 3 is a schematic diagram illustrating a thermopile, an instrumentation amplifier, and heater control circuitry included in the convective accelerometer of Fig. 2;

Fig. 4 is a schematic diagram illustrating a chopper amplifier included in the instrumentation amplifier of Fig. 3;

Fig. 5a is a schematic diagram illustrating a switched capacitor filter and a class AB output stage included in the convective accelerometer of Fig. 2;

Fig. 5b is a timing diagram illustrating clock signals used by the switched capacitor filter of Fig. 5a;

Fig. 6 is a schematic diagram illustrating a clock generator included in the device of Fig. 1;

Fig. 7 is a schematic diagram illustrating a reference voltage/temperature sensor circuit included in the device of Fig. 1;

Fig. 8 is a plan view of a control register of a control circuit included in the device of Fig. 1; and

Fig. 9 is a flow diagram illustrating a method of regulating power dissipated in an acceleration sensor included in the convective accelerometer of Fig. 2.

10 DETAILED DESCRIPTION OF THE INVENTION

Fig. 1 is a plan view of an illustrative embodiment of an integrated circuit ("chip") 100 comprising a silicon micro-machined convective accelerometer device according to the present invention. As depicted in Fig. 1, the chip 100 includes a clock generator 118, a voltage reference/temperature sensor 120, a control circuit 122, and a convective accelerometer 124. The chip 100 further includes a plurality of input pads, i.e., an SCK pad 110 and a DI pad 112; a plurality of output pads, i.e., a TOUT pad 114 and a AOUT pad 116; a plurality of voltage pads, i.e., an RBIAS pad 108 and a Vdd pad 102; and, a plurality of ground pads, i.e., a Vsa pad 104 and a Vsd pad 106.

In the illustrated embodiment, the convective accelerometer 124 includes a thermal acceleration sensor and associated signal conditioning circuitry to provide an output voltage at the AOUT pad 116 representative of the magnitude of acceleration along a predetermined axis. In a preferred embodiment, the signal conditioning circuitry associated with the acceleration sensor utilizes a plurality of converter or "chopper" amplifiers, a plurality of switch capacitor circuits, and a sigma-delta modulator.

Accordingly, the clock generator 118 provides a plurality of clock signals, i.e., a Ck\_ca signal on a line 130, a Ck\_sc signal on a line 128, and a Ck\_osc signal on a line 136 (see also Fig. 2) to the convective accelerometer 124 for use by the chopper amplifiers, the switched capacitor circuits, and the sigma-delta modulator, respectively. For example, the clock generator 118 may generate the Ck\_ca, Ck\_sc, and Ck\_osc signals using an oscillator included in the clock generator 118. Alternatively, the Ck\_ca, Ck\_sc, and Ck\_osc signals may be generated using an external oscillator coupled to the SCK pad 110.

The reference voltage/temperature sensor 120 includes a band-gap voltage reference and associated voltage and current bias generation circuitry to provide a reference voltage, i.e., a voltage, Vbs, on a line 132 (see also Fig. 2) to the convective accelerometer 124 and the clock generator 118 for use as an analog common reference point and/or to bias circuits included therein independent of the supply voltage, Vdd. The current bias generator associated with the band-gap voltage reference comprises an external pull-down resistor coupled to the RBIAS pad 108. Further, the reference voltage/temperature sensor 120 includes a Proportional To Absolute Temperature (PTAT) current source to provide an output voltage at the TOUT pad 114 representative of the absolute temperature of the chip 100.

The control circuit 122 includes a control register that provides control data, i.e., Cntl data comprising a plurality of bits on a control bus 134 (see also Fig. 2) to the clock generator 118, the reference voltage/temperature sensor 120, and the convective accelerometer 124 for use in determining settings of calibration adjustments and

configuration switches included therein. The Cntl data is serially input to the control register by way of the DI pad 112. For example, the calibration adjustments included in the clock generator 118, the reference voltage/temperature sensor 120, and the convective accelerometer 124 may be implemented as programmable trimmer potentiometers having resistive values that are programmed by way of predetermined Cntl words provided by the control circuit 122 on the control bus 134.

10 In a preferred embodiment, the chip 100 is fabricated using a 0.6  $\mu\text{m}$ , double-polysilicon, double-metal (*i.e.*, aluminum, Al), n-well CMOS process. However, it should be understood that other suitable processes for fabricating silicon micro-machinable semiconductor devices may also be used.

15 Although Fig. 1 does not explicitly depict power bus routing between the power-related pads 102, 104, and 106 and the circuit blocks 118, 120, 122, and 124, it should be understood that the single supply voltage, Vdd, is used by both digital and analog portions of the convective accelerometer device; the ground potential, Vsd, is used as digital ground in the convective accelerometer device; and, the ground potential, Vsa, is used for generating analog voltage levels in the convective accelerometer device. For example, the power bus routing may be implemented on the chip 100 using conventional techniques such as those used to limit positive rail noise and minimize corruption of ground potentials. The circuit blocks 118, 120, 122, and 124 along with their respective connections to the power-related pads 102, 104, and 106 will be explained in further detail below.

Fig. 2 depicts a block diagram of the convective accelerometer 124, which includes a heater control circuit 202, a thermopile/heater 204, an instrumentation amplifier 206, an SC filter 208, and a class AB output stage 209.

5 Specifically, as shown in Fig. 3, the thermopile/heater 204 includes an array of thermocouples 302 and 306, which are coupled at one end and provide a differential output voltage across lines 222 and 224 at respective opposite ends. Further, the thermocouples 302 and 306 are disposed on  
10 opposing sides of a heater element, which in a preferred embodiment is a heater resistor 304.

In this illustrative embodiment, the thermocouples 302 and 306 and the heater resistor 304 are formed using conventional CMOS processing. For example, the  
15 thermocouples 302 and 306 may be formed by aluminum and polysilicon layers disposed on a silicon substrate surface of the chip 100; and, the heater resistor 304 may be formed by the polysilicon layer disposed on the substrate surface. Further, in order to form the acceleration sensor of the  
20 convective accelerometer device, an enclosed chamber is formed by micro-machining the substrate surface of the chip 100 to create a cavity; and, the heater resistor 304 is suspended across the cavity with the thermocouples 302 and 306 disposed in the cavity on opposing sides of the heater  
25 resistor 304. In this illustrative embodiment, the fluid providing the convective heat transfer in the enclosed chamber comprises a quantity of air. Accordingly, an acceleration sensitive axis passes perpendicularly through the heater resistor 304 and the thermocouples 302 and 306  
30 disposed on opposing sides thereof, and the differential output voltage of the thermocouples 302 and 306 provided

across the lines 222 and 224 is proportional to the magnitude of acceleration applied along this axis.

Those of ordinary skill in the art will appreciate that the average of the common-mode output voltage of the thermopile comprising the thermocouples 302 and 306 is proportional to the power dissipated in the heater resistor 304, and that the sensitivity of the acceleration sensor included in the convective accelerometer 124 generally varies according to the square of the heater power at low power levels and is generally proportional to the heater power at higher power levels. In this illustrative embodiment, the sensitivity of the convective accelerometer 124 is held at a desired value over power supply voltage variations and/or heater resistor make tolerances by closed-loop control of the common-mode voltage drop across the thermocouples 302 and 306, which is a measure of the temperature gradient produced by the heater resistor 304.

Specifically, the common-mode voltage drop across the thermocouples 302 and 306 is set to a desired level using a voltage divider circuit comprising a calibration adjustment 312 connected at one end to the reference voltage,  $V_{bs}$ , and connected in series at an opposing end to a resistor 314, which in turn is coupled to the ground potential,  $V_{sa}$ . Further, the common node of the calibration adjustment 312 and the resistor 314 is connected to the coupled ends of the thermocouples 302 and 306.

Accordingly, the desired common-mode voltage drop across the thermocouples 302 and 306 is set by providing a predetermined Cntl word to the calibration adjustment 312 of the voltage divider via the control bus 134, thereby setting the voltage level at the coupled ends of the thermocouples

302 and 304. The instrumentation amplifier 206 extracts the common-mode output voltage from the voltage provided across the lines 222 and 224, and provides the common-mode output voltage to the heater control 202 on a line 220.

5       The difference between the common-mode output voltage on the line 220 and the reference voltage,  $V_{bs}$ , is integrated by a switched-capacitor integrator including an operational amplifier 338, a switched input capacitor 336, and an integrating capacitor 340. The output of the  
10       integrator is provided to a sigma-delta modulator 342, which generates a pulse density stream that has an average value that is proportional to the output voltage of the integrator. The pulsed output voltage is used to control the common-mode voltage drop across the thermocouples 302  
15       and 306 by turning "on" and "off" a switch transistor 308, which causes the heater resistor 304 to either be open or have the entire power supply voltage across it. In a preferred embodiment, the common-mode voltage drop across the thermocouples 302 and 306 is regulated using Pulse-  
20       Density Modulation (PDM). In an alternative embodiment, the common-mode voltage drop across the thermocouples 302 and 306 is regulated using Pulse-Width Modulation (PWM).

As described above, the common-mode voltage drop across the thermocouples 302 and 306 is a measure of the  
25       temperature gradient produced by the heater resistor 304. It is noted that in some cases the temperature gradient and therefore the sensitivity of the acceleration sensor are proportional to the power dissipated in the heater resistor 304. When the control loop is regulating, the common-mode  
30       output voltage of the thermocouples 302 and 306 will be equal to  $V_{bs}$ . The common-mode voltage drop across the

thermocouples 302 and 306 is the voltage difference between Vbs and the voltage at the common point of the thermocouples 302 and 306. In those cases where the sensitivity of the acceleration sensor is proportional to the power dissipated in the heater resistor 304, the voltage at the common point of the thermocouples 302 and 306 can be set by the predetermined Cntl word to allow the power dissipation in the heater resistor 304 and therefore the accelerometer sensitivity to be set to a desired value.

Specifically, the pulsed output voltage of the heater control 202 is used to switch a pass transistor 308 "on" and "off." In a preferred embodiment, the pass transistor 308 is a CMOS n-channel transistor. One terminal of the heater resistor 304 is connected to the supply voltage, Vdd, and another terminal of the heater resistor is coupled to a drain connection of the pass transistor 308. Further, the source connection of the pass transistor 308 is connected to the ground potential, Vsa; and, the gate connection of the pass transistor 308 is connected to the pulsed output voltage of the heater control 202 on the line 230 by way of a inverter buffer 310.

Accordingly, when the pass transistor 308 is switched "on" by the pulsed output voltage of the heater control 202, i.e., when a high logic level of the inverted, pulsed output voltage is applied to the gate connection of the pass transistor 308, current flows through the heater resistor 304 and the pass transistor 308 to the ground potential, Vsa. Alternatively, when the pass transistor 308 is switched "off" by the pulsed output voltage, i.e., when a low logic level of the inverted, pulsed output voltage is applied to the gate connection of the pass transistor 308,

no current flows through the heater resistor 304. Because the pulse density of the pulsed output voltage switching the pass transistor 308 "on" and "off" is proportional to the common-mode voltage drop across the thermocouples 302 and 306, the average power provided to the heater resistor 304 from the supply voltage, Vdd, through the pass transistor 308 can be set by setting the voltage at the thermocouple common point using the above-described voltage divider circuit. It should be noted that, in an alternative embodiment, the heater control 202 may provide a continuous output to the thermopile/heater 204 for regulating the current through the heater resistor 304.

As shown in Fig. 3, the instrumentation amplifier 206 includes a differential input stage comprising an operational amplifier ("OpAmp") 316, an input resistor 320, and a feedback resistor 322; and, an OpAmp 318, an input resistor 324, and a feedback resistor 326. In a preferred embodiment, the OpAmps 316 and 318 are chopper amplifiers. The instrumentation amplifier 206 further includes a differential-to-single-ended output stage comprising an OpAmp 328, input resistors 330, 332, and 336, and a feedback resistor 334.

The instrumentation amplifier 206 amplifies the differential output voltage provided by the thermopile/heater 204 across the lines 222 and 224, and converts the differential output voltage to a single-ended output voltage referenced to the analog common reference point, Vbs, on a line 226. The instrumentation amplifier 206 also provides the common-mode output voltage of the thermocouples 302 and 306 to the heater control 202 on the

line 220 for use in regulating the average power provided to the heater resistor 304.

In an exemplary configuration of the convective accelerometer device, the sensitivity of the thermopile comprising the thermocouples 302 and 306 is 5 mV/°C; the sensitivity of the acceleration sensor is 0.05°C/g; and, a corresponding sensitivity at the AOUT pad 116 is 50 mV/g. Accordingly, an acceleration of 10 g applied along the acceleration sensitive axis results in a differential output voltage of 5 mV/°C x 0.05°C/g x 10 g, or 2.5 mV across the lines 222 and 224. This produces a sensitivity of 2.5 mV/10 g, or 0.25 mV/g at the output of the thermopile/heater 204. In order to achieve the sensitivity of 50 mV/g at the AOUT pad 116, a combined gain of the instrumentation amplifier 206 and the SC filter 208 is therefore equal to 200. In this exemplary configuration, the instrumentation amplifier 206 has a gain of 100 and the SC filter 208 has a gain of 2 to achieve the combined gain of 200 at the AOUT pad 116. It is noted that the instrumentation amplifier 206 provides the common-mode output voltage to the heater control 202 with unity gain.

In a preferred embodiment, the OpAmp 316 and the resistors 320 and 322, and the OpAmp 318 and the resistors 324 and 326 of the instrumentation amplifier 206 form a pair of non-inverting gain stages, each having the exemplary gain of 100. This means that the differential-to-single-ended output stage comprising the OpAmp 328 and the resistors 330, 332, 334, and 336 has unity gain. In order to achieve the relatively large closed-loop gain of 100, the OpAmps 316 and 318 are preferably implemented as identical chopper amplifiers.

Fig. 4 depicts a schematic diagram of the chopper amplifier 316. Specifically, the chopper amplifier 316 includes a first stage comprising a common-source/common-gate amplifier configuration; and, second and third stages, each comprising a common-source amplifier configuration. Further, a chopper switch 424 is provided at the input of the first stage, and a chopper switch 426 is provided between the first stage and the second stage of the chopper amplifier 316.

The common-source/common-gate amplifier configuration of the first stage of the chopper amplifiers 316 and 318 improves voltage gain for achieving the relatively large closed-loop gain of 100. Further, in the above-mentioned exemplary configuration, the Ck\_ca signal clocking the chopper switches 424 and 426 has a nominal frequency of 25 kHz. As a result, any offset and/or low-frequency noise produced by the chopper amplifiers 316 and 318 are modulated at the chopper frequency of 25 kHz and subsequently removed by the low-pass SC filter 208 (see Fig. 2).

Suitable bias voltages Vb1, Vb2, Vb3, and Vb4 are provided at gate connections of p-channel transistors 402, 404, 406, and 408; p-channel transistors 410, 412, and 414; n-channel transistors 416 and 418; and, an n-channel transistor 420, respectively. For example, the Vb1, Vb2, Vb3, and Vb4 bias voltage levels may be generated using a voltage bias generator 740 (see Fig. 7) included in the reference voltage/temperature sensor 120 (see Fig. 1).

Further, the chopper amplifiers 316 and 318 are frequency compensated using capacitors 422 and 424 and nested Miller compensation techniques. In the exemplary configuration, the chopper amplifiers 316 and 318 are

overcompensated to provide, at the exemplary gain of 100, low-pass filters with poles at a nominal frequency of 5 kHz. The low-pass filtering performed by the non-inverting gain stages including the chopper amplifiers 316 and 318  
5 therefore band-limits any thermal noise that might otherwise be shifted-down to the pass-band by aliasing at the SC filter 208.

As shown in Fig. 3, the heater control 202 includes a switched capacitor integrator stage comprising a switched  
10 capacitor 336 and associated switches (not numbered), an OpAmp 338, and a feedback capacitor 340; and, a sigma-delta modulator 342, which is preferably a first-order sigma-delta modulator. For example, the switches associated with the switched capacitor 336 may be implemented using CMOS  
15 transmission gates; and, the complementary Ck\_sc signals controlling the CMOS transmission gates may be implemented as non-overlapping clock phases. In the exemplary configuration, the Ck\_sc signal has a nominal frequency of 50 kHz; and, the Ck\_osc signal clocking the sigma-delta  
20 modulator 342 has a nominal frequency of 800 kHz.

The switched capacitor integrator stage amplifies and low-pass filters the common-mode output voltage of the thermocouples 302 and 306 provided by the instrumentation amplifier 206 on the line 220, and provides an amplified and  
25 filtered output voltage to the sigma-delta modulator 342. For example, to ensure stability of the feedback circuit comprising the heater control 202, the feedback circuit may be compensated using the dominant pole provided by the switched capacitor integrator stage. Moreover, in order to  
30 achieve optimal phase margin, the switched capacitor

integrator stage is implemented as a non-inverting stage having a relatively low unity gain frequency, e.g., 5 Hz.

5 The sigma-delta modulator 342 generates the above-mentioned pulsed output voltage, which has a pulse density proportional to the integrator output voltage, and provides the pulsed output voltage to the inverter buffer 310 of the thermopile/heater 204 on the line 230. Specifically, the common-mode output voltage of the thermocouples 302 and 306 is set to the desired level, and the heater control 202 provides negative feedback between the instrumentation amplifier 206 and the thermopile/heater 204 that causes the average density of the pulsed output voltage to track the desired common-mode output voltage level. The inverter 310 buffers and inverts the pulsed output voltage, and provides 15 the inverted pulse sequence to the gate connection of the pass transistor 308, thereby regulating the average power provided to the heater resistor 304. Because the pulsed output voltage is inverted by the inverter 310, the pulse density applied to the pass transistor 308 is a decreasing function of the difference between the common-mode voltage and the analog common reference point. 20

It should be noted that switching the pass transistor 308 "on" and "off" using the pulse sequence generated by the sigma-delta modulator 342 causes the power provided to the heater resistor 304 from the supply voltage, Vdd, through the pass transistor 308 to be pulsed. In the above-mentioned exemplary configuration, the accelerometer sensor comprising the heater resistor 304 and the thermocouples 302 and 306 has a relatively low-frequency double pole at about 25 80 Hz. Accordingly, in the exemplary configuration, the acceleration sensor attenuates the high frequency content of 30

the pulsed power provided to the heater resistor 304, thereby averaging the heater power to provide substantially constant voltages across the lines 222 and 224. The relatively high frequency of the Ck\_osc signal clocking the sigma-delta modulator 342 increases this attenuation. It is also noted that switching the pass transistor 308 "on" and "off" as described above reduces the power dissipated by the pass transistor 308.

If the heater resistor 304 fails, e.g., if the failed heater resistor 304 causes an open circuit between the supply voltage, Vdd, and the drain connection of the pass transistor 308, then the heater control 202 will be incapable of regulating the power in the acceleration sensor. For example, such a failure may cause the output voltage of the switched capacitor integrator stage to swing to the ground potential, Vsa. In this illustrative embodiment, the output voltage of the switched capacitor integrator stage is continuously compared with a threshold voltage near the ground potential, Vsa; and, when the integrator output voltage passes through the threshold voltage, a "Fail" signal is generated to indicate the failure of the acceleration sensor.

Fig. 5a depicts schematic diagrams of the SC filter 208 and the class AB output stage 209 included in the convective accelerometer 124. Specifically, the SC filter 208 includes an OpAmp 510, a feedback capacitor 512, and a plurality of switched capacitors 514, 516, and 518 and associated switches (not numbered); and, the class AB output stage 209 includes an OpAmp 520, input resistors 526 and 528, and calibration adjustments 522 and 524.

5 The switches associated with the switched capacitors 514, 516, and 518 may be implemented using CMOS transmission gates. Further, the switches associated with the switched capacitor 514 are controlled by the non-overlapping, complementary Ck\_sc signals; the switches associated with the switched capacitor 516 are controlled by the complementary Ck\_sc signals, a Ck\_A clock signal, and a Ck\_B clock signal; and, the switches associated with the switched capacitor 518 are controlled by the complementary Ck\_sc signals, a Ck\_C clock signal, and a Ck\_D clock signal. Fig. 5b depicts the relative timing of the complementary Ck\_sc signals; and, the Ck\_A, Ck\_B, Ck\_C, and Ck\_D signals. For example, the Ck\_A, Ck\_B, Ck\_C, and Ck\_D signals may be derived from the complementary Ck\_sc signals using conventional techniques.

15 In the above-mentioned exemplary configuration, the SC filter 208 has a pole at a nominal frequency of 100 Hz. Further, the switched capacitors 516 and 518 are controlled to generate a notch in the output voltage of the SC filter 208 at the chopping frequency of 25 kHz. Still further, values of the feedback capacitor 512 and the switched capacitors 514, 516, and 518 are chosen to provide the exemplary gain of 2.

25 The SC filter 208 amplifies and low-pass filters the output voltage provided by the instrumentation amplifier 206 on the line 226 to remove the low-frequency noise produced by the chopper amplifiers 316 and 318 and the thermal noise generated in the convective accelerometer device, and provides an amplified and filtered output to the class AB output stage 209.

The calibration adjustments 522 and 524 of the class AB output stage 209 are used for calibrating output gain and offset, respectively, of the convective accelerometer device. Specifically, the output gain is calibrated by providing a predetermined Cntl word to the calibration adjustment 522, and the output offset is similarly calibrated by providing a predetermined Cntl word to the calibration adjustment 524, via the control bus 134.

Fig. 6 depicts a schematic diagram of the clock generator 118 (see also Fig. 1). Specifically, the clock generator 118 includes a current source 618 and switches 622 and 630 for charging and discharging a capacitor 626; a current source 620 and switches 624 and 632 for charging and discharging a capacitor 628; comparators 614 and 616 coupled to the capacitors 626 and 628, respectively, and a band-gap reference voltage, Vbgs (see Fig. 7); an SR latch comprising NAND gates 610 and 612; frequency dividers 634 and 636; and, a configuration switch 638 for selectively providing either the output of the SR latch or a clock signal produced by the external oscillator to the frequency divider 634. For example, the current sources 618 and 620 may be implemented using a current bias generator 742 (see Fig. 7) and the external resistor coupled to the RBIAS pad 108 (see Fig. 1); and, the switches 622, 630, 624, and 632 may be implemented using suitable respective pass transistors. The switches 624 and 630 are controlled by the Ck\_osc signal, and the switches 622 and 632 are controlled by the complement of the Ck\_osc signal.

Accordingly, if the Ck\_osc signal is initially at a low logic level, then the switch 632 is actuated to discharge the capacitor 628 to the ground potential, Vsa, and the

switch 622 is actuated to charge the capacitor 626. When the capacitor 626 is charged to a voltage level greater than the band-gap reference voltage level,  $V_{bgs}$ , the output state of the comparator 614 transitions from a high logic level to the low logic level, thereby transitioning the output state of the NAND gate 610 from the low logic level to the high logic level. As a result, the  $Ck\_osc$  signal is now at the high logic level, thereby actuating the switch 630 to discharge the capacitor 626 to the ground potential,  $V_{sa}$ , and actuating the switch 624 to charge the capacitor 628. When the capacitor 628 is charged to a voltage level greater than the band-gap reference voltage level,  $V_{bgs}$ , the output state of the comparator 616 transitions from the high logic level to the low logic level, thereby transitioning the output state of the NAND gate 610 from the high logic level to the low logic level. In this way, the capacitors 626 and 628 are periodically charged and discharged for internally generating the  $Ck\_osc$  clock signal on the line 136 (see also Fig. 1).

In the above-mentioned exemplary configuration, the values of the currents provided by the current sources 618 and 620 and the values of the capacitors 626 and 628 are selected to generate the  $Ck\_osc$  signal with the nominal frequency of 800 kHz.

The configuration switch 638 is set by providing a predetermined  $Cntl$  word to the calibration switch 638 via the control bus 134 to select either the internally generated clock signal or the clock signal generated by the external oscillator coupled to the SCK pad 110. As a result, the internally generated clock signal or the externally generated clock signal is provided to the

frequency divider 634, which divides the frequency of either one of these clock signals by sixteen (16) to generate the Ck\_sc signal. The frequency divider 636 then divides the Ck\_sc signal at its input by two (2) to generate the Ck\_ca  
5 signal. In the exemplary configuration, the Ck\_osc signal has the nominal frequency of 800 kHz, thereby causing the Ck\_sc and Ck\_ca signals to have the nominal frequencies of 50 kHz and 25 kHz, respectively.

Fig. 7 depicts a schematic diagram of the reference  
10 voltage/temperature sensor 120 (see also Fig. 1). Specifically, the reference voltage/temperature sensor 120 includes an OpAmp 708; p-channel transistors 702, 704, and 706; n-channel transistors 718 and 720; bipolar junction transistors 714 and 716; and, resistors 710 and 712 to  
15 provide the band-gap reference voltage, Vbgs, on the line 746. For example, the bipolar junction transistors 714 and 716 may be implemented as vertical, common-collector transistors. In the above-mentioned exemplary configuration, the band-gap reference voltage, Vbgs, has a  
20 value of about 1.2 volts.

The reference voltage/temperature sensor 120 further includes a voltage divider comprising serially coupled resistors 750 and 752 connected between the supply voltage, Vdd, and the ground potential, Vsa; and, a configuration  
25 switch 722 for selectively providing either the voltage level, Vrs, at the common node of the resistors 750 and 752 or the band-gap reference voltage, Vbgs, on the line 746 to the voltage bias generator 740. The configuration switch 722 is set by providing a predetermined Cntl word to the  
30 calibration switch 722 via the control bus 134 to select either the Vrs or Vbgs voltage level. The selected voltage

level is then provided to the voltage bias generator 740, which provides the reference voltage,  $V_{bs}$ , on the line 132 (see also Fig. 1).

In the exemplary configuration, if the configuration switch 722 is set to provide the  $V_{bgs}$  voltage level to the voltage bias generator 740, then the convective accelerometer 124 (see Fig. 1) operates in an absolute mode and the reference voltage,  $V_{bs}$ , has a value of about 1.0 volts. Alternatively, if the configuration switch 722 is set to provide the  $V_{rs}$  voltage level to the voltage bias generator 740, then the convective accelerometer 124 operates in a ratiometric mode and the reference voltage,  $V_{bs}$ , has a value of about one-third of the supply voltage,  $V_{dd}$ . In this illustrative embodiment, the convective accelerometer 124 is also made less sensitive to power fluctuations by setting the reference voltage,  $V_{bs}$ , to the fixed value of 1.0 volts. It should be noted that when the convective accelerometer 124 operates in the ratiometric mode with the reference voltage,  $V_{bs}$ , set to the  $V_{rs}$  voltage level, the sensitivity of the acceleration sensor is proportional to the supply voltage level,  $V_{dd}$ .

Still further, the reference voltage/temperature sensor 120 includes a current mirror comprising the n-channel transistors 718 and 720 for providing a PTAT current,  $I_{PTAT}$ , on a line 754. The PTAT current,  $I_{PTAT}$ , is provided to a current-to-voltage converter comprising an OpAmp 726 and calibration adjustments 724 and 730 to generate an output voltage at the TOUT pad 114 (see Fig. 1) that is proportional to  $I_{PTAT}$ , which in turn is proportional to the absolute temperature of the chip 100. In this illustrative embodiment, the convective accelerometer 124 is made less

sensitive to temperature fluctuations by providing the output voltage at the TOUT pad 114 to temperature compensation circuits either external to or on the same substrate as the convective accelerometer 124 to compensate for changes in the temperature of the chip 100 and/or the local environment.

The calibration adjustments 724 and 730 of the current-to-voltage converter are used for calibrating output gain and offset, respectively, of the temperature sensor 120. Specifically, the output gain is calibrated by providing a predetermined Cntl word to the calibration adjustment 724, and the output offset is similarly calibrated by providing a predetermined Cntl word to the calibration adjustment 730, via the control bus 134.

Fig. 8 depicts a 22-bit control register 800 included in the control circuit 122 (see Fig. 1) for providing the Cntl data to the clock generator 118, the reference voltage/temperature sensor 120, and the convective accelerometer 124 to determine the settings of the calibration adjustments 312, 522, 524, 724, and 730, and the configuration switches 638 and 722. As described above, the Cntl data is serially input to the control register 800 via the DI pad 112 (see Fig. 1) and output in parallel on the control bus 134.

In the above-mentioned exemplary configuration, the twenty-two (22) control bits are defined as follows:

C0	Determines the setting of the configuration switch 722. For example, if C0 = 0, then Vbs = Vbgs; and, if C0 = 1, then Vbs = Vrs.
C1	Determines the setting of the configuration switch 638. For example, if C1 = 0, then Ck_osc, Ck_sc, and Ck_ca are generated by the internal clock; and, if C1 = 1, then Ck_osc, Ck_sc, and Ck_ca are generated by the external clock.
C2-C5	Determine the setting of the calibration adjustment 724. For example, the Cntl word "C2-C5" may be interpreted as a 2's complement number with "0000" representing a nominal trim setting.
C6-C9	Determine the setting of the calibration adjustment 730. For example, the Cntl word "C6-C9" may be interpreted as a 2's complement number with "0000" representing a nominal trim setting.
C10-C13	Determine the setting of the calibration adjustment 522. For example, the Cntl word "C10-C13" may be interpreted as a 2's complement number with "0000" representing a nominal trim setting.
C14-C17	Determine the setting of the calibration adjustment 524. For example, the Cntl word "C14-C17" may be interpreted as a 2's complement number with "0000" representing a nominal trim setting.
C18-C21	Determine the setting of the calibration adjustment 312. For example, the Cntl word "C18-C21" may be interpreted as a 2's complement number with "0000" representing a nominal trim setting.

An illustrative method of regulating the thermopile common-mode voltage and therefore the temperature gradient produced by the heater using the above-described feedback circuit is illustrated by reference to Fig. 9. As depicted in step 902, the calibration adjustment 312 is adjusted to set the voltage level at the coupled ends of the

thermocouples 302 and 306. In a preferred embodiment, this voltage level is adjusted to be slightly less than the reference voltage,  $V_{bs}$ . Further, the polarities of the thermocouples 302 and 306 are such that an increase in the power delivered to the heater resistor 304 causes increasingly positive output voltages to be applied to lines 222 and 224, respectively, at the input of the instrumentation amplifier 206. It should be noted that in the absence of acceleration, the respective output voltages on the lines 222 and 224 are equal because of the symmetrical configuration of the acceleration sensor. The average of the common-mode output voltage of the thermopile comprising the thermocouples 302 and 306 is then provided, as depicted in step 904, by the instrumentation amplifier 206 to the switched capacitor integrator stage. Next, an amplified and filtered voltage is provided, as depicted in step 906, by the switched capacitor integrator stage to the sigma-delta modulator 342. A pulsed output voltage having a pulse density proportional to the integrator output voltage is then provided, as depicted in step 908, by the sigma-delta modulator 342 to the pass transistor 308 to regulate the thermopile common-mode voltage. When the control loop is regulating, the power dissipated in the heater resistor 304 will cause the average of the common-mode output voltage of the thermopile to be equal to  $V_{bs}$ . In the case where the power dissipated in the heater resistor 304 is proportional to the common-mode voltage drop across the thermocouples 302 and 306, the heater power can be controlled by changing the voltage at the thermocouple common point through the adjustment 312.

5